Monolithically Integrated Solid-State Terahertz Transceivers

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Motivation—The "unconventional" terahertz (THz) frequency electromagnetic spectrum offers disruptive advantages for security, defense, scientific, and industrial missions. However, THz solid-state technology remains immature compared to microwave electronics and infrared photonics. A central component of THz technology, a heterodyne transceiver, has until now relied on large, high-maintenance gas- or vacuum-tube sources to supply coherent THz radiation of sufficient power and mechanically aligned optical coupling to deliver power to a THz receiver. Clearly any widely practical THz system requires an integrated semiconductor-based technology. Only recently has this become realistic with the invention of high-power microelectronic THz quantum cascade lasers (QCLs). This project's goal was to integrate a QCL and diode mixer onto a single chip. The result is the first true THz integrated circuit (IC) that performs all the functions of existing THz transceivers but at a small fraction of the size and in a robust platform scalable to semiconductor fabrication production.

Accomplishment—The starting point for this integrated transceiver exploits a structural advantage unique to QCLs. In a THz QCL, at least one of the metal contacts is nearly in direct contact with the optically active region and hence has large overlap with the optical mode. Our transceiver capitalizes on this overlap to literally embed a small Schottky diode mixer into the ridge waveguide cavity of a QCL, as depicted in Fig. 1. Here the semiconductor cathode of the Schottky diode and the top bias contact of the QCL ridge waveguide share the same *n*+ doped GaAs layer. The QCL top (ground) contact is made using an ohmic metal while the diode is made using a Schottky metal. This integration strategy takes advantage of the fact that the QCL ridge waveguide cavity's *internal* electric field is strongest near the metal-semiconductor interface and thus permeates the diode's cathode. The internal field modulates the width of the diode's depletion region, leading to mixing of the THz signals. An image of a completed transceiver is shown in Fig. 2. After processing, the lasing characteristics of the QCL showed no significant degradation in power or threshold bias conditions, thus confirming operation as a coherent transmitter. Operation of the THz IC as a heterodyne receiver was also explicitly demonstrated. An external signal was supplied by a molecular gas laser, using the 2.841143 THz line of difluoromethane. Heterodyne reception of the external signal was clearly observed at the output of the Schottky diode, which generated down-converted microwave signals at difference frequencies between several of the QCL's internal Fabry-Perot (F-P) modes and the external molecular gas line. The F-P difference frequency generated by the diode was also be used as an active feedback signal to phase lock the difference modes of the QCL to a microwave reference and hence maintain constant mode spacing to high precision. The THz IC significantly simplifies the ability to phase lock by eliminating optical coupling between physically separate components.

Significance—Widespread use of the THz spectrum outside the laboratory has awaited a viable solid-state technology platform. The monolithically integrated solid-state THz transceiver developed here represents a broadly applicable answer to this technological challenge in the form of the first working THz IC. Such a transceiver IC is the initial step towards higher stages of chip-level integration of multiple THz functionalities in a miniature, reliable, and scalable platform.

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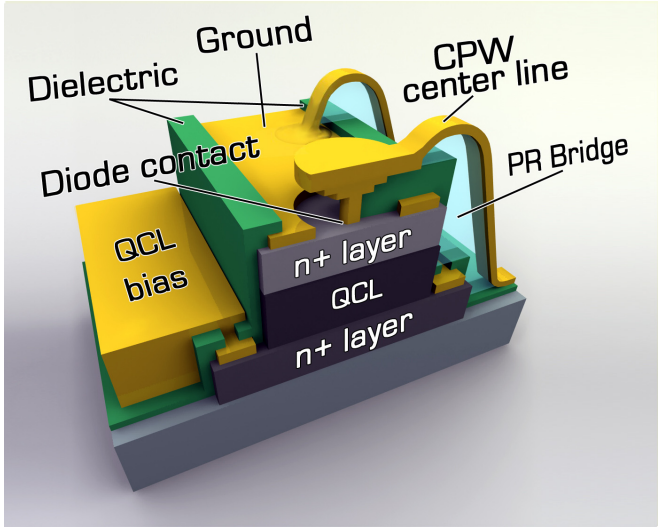

Figure 1. Design drawing showing the Schottky diode position atop a QCL ridge waveguide and ground-signal-ground co-planar waveguide (CPW) contacts to the diode mixer. Some of the insulating layer under the diode (green) and the photoresist (PR) bridge (light blue) have been cut-away for clarity.

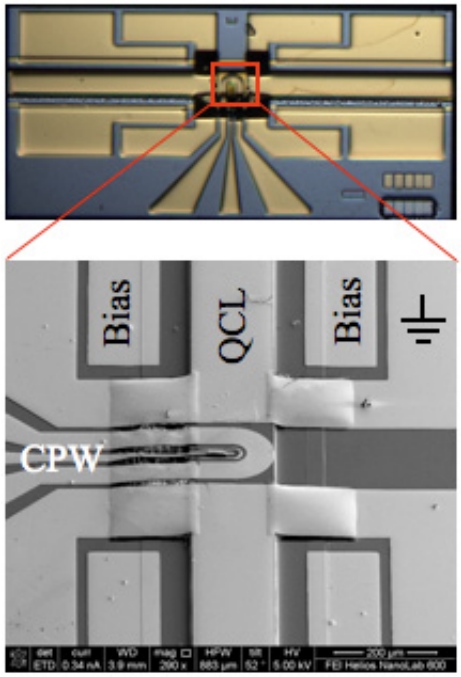

Figure 2. (top) Optical microscope plan view image of a complete THz transceiver IC with all electrical contacts, and (bottom) expanded focused ion-beam image showing the CPW contact configuration to the Schottky diode anode.